

1920
H25

J. W. Harsch

Alloys of Tungsten by Diffusion

ALLOYS OF TUNGSTEN BY DIFFUSION

BY

JOHN WILLIAM HARSCH

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

CHEMICAL ENGINEERING

COLLEGE OF LIBERAL ARTS AND SCIENCES

UNIVERSITY OF ILLINOIS

1920

1920
H25

UNIVERSITY OF ILLINOIS

..... May 27, 1920

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

..... JOHN WILLIAM HARSCH

ENTITLED..... ALLOYS OF TUNGSTEN BY DIFFUSION

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF..... BACHELOR OF SCIENCE

..... IN CHEMICAL ENGINEERING

..... D. F. McFarland

Instructor in Charge

APPROVED:.....

W. A. Hayes

HEAD OF DEPARTMENT OF.....

Chemistry

453040

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ACKNOWLEDGMENT.

This investigation was undertaken at the suggestion of Dr. D. F. McFarland, and was done under his direction. I take this opportunity to thank him sincerely for his advice, encouragement, and constant interest throughout the work. I also take this opportunity of thanking the Fansteel Products Company for their help in securing the materials used in these experiments.

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ALLOYS OF TUNGSTEN BY DIFFUSION

I. Introduction.

1. The Purpose of the Investigation.

The purpose of this investigation may be summed up under three heads.

(1) To study microscopically the diffusion of various metals, both in the liquid and solid state, into tungsten in the solid state, or of the tungsten into the metals.

(2) To determine, if possible, in those cases where alloys are formed, the relation of the metals to each other; that is, whether solid solutions, eutectic alloys, or compounds are formed.

(3) To study the formation of carbides and of the double carbides of iron and chromium in an attempt to case-harden tungsten.

2. Historical and General Status of the Field.

(1) Diffusion in strictly metallic systems.

It is not the purpose to discuss here the previous work done upon each of the various systems which have been taken up in this investigation, inasmuch as this will be considered later in direct connection with the discussion of the results here obtained.

The phenomenon of diffusions in metals, according to C. H. Desch¹, who has summarized the work up to 1912, has been known and worked upon since the time of Faraday, who showed that the

¹ C. H. Desch, Chem. News, 106, p. 168

welding of platinum and iron below their melting points is due to the diffusion of the metals to form a solid solution. In "The Electro Deposition of Metals", Langbein and Brann¹ state that a thin layer of copper or brass, electrolytically deposited on zinc, slowly disappears into the zinc, leaving the original greyish white surface of the metal.

W. Spring² began the most systematic investigation of diffusion. Perhaps the most interesting phase of his work was the formation of brass by the compression of a mixture of copper and zinc filings. Later³ Spring began a series of investigations in which he used two cylinders of the same metal accurately fitted together and free from grease. He was able to obtain a union at ordinary temperatures which, on heating, became so firm that the junction proved of greater strength than the metal itself. Like experiments were then carried out with two cylinders of different metals, and similar results were obtained, with the formation of an alloy at the junction. These results have since been confirmed by the work of other investigators.

The classical example of diffusion, however, was in the work started by Roberts-Austen⁴, in which he, using lead and a 5% gold-lead alloy, found that the gold diffused upward into the lead against the force of gravity. The experiments were carried on at 165° C. for thirty days, and the gold in the lead was determined by assay. Other investigators, following his lead, carried out

¹ G. Langbein and W. T. Brann, The Electro Deposition of Metals, Philadelphia, (1891) p. 133

² W. Spring, Ber xv. (1882) p. 595

³ W. Spring, Zeit, Phys. Chem. xv. (1894) p. 73

⁴ Roberts-Austen, Phil. Trans. 187, (1896) A 383

experiments at different temperatures and calculated, from experiments lasting four years, that diffusion at 18° C. in one thousand years, would equal that in molten lead in one day.

The more recent experiments are those of Bruni and Meneghini¹, in which these men heated a nickel wire, electrolytically coated with copper until it corresponded to 59% copper and 41% nickel, at 1000° C. in an atmosphere of hydrogen, and, by measuring the conductivity of the wire, they were able to follow the progress of diffusion. They found that a homogeneous alloy was formed after 140 hours. Similar work was carried out with other metals and at other temperatures with like results.

Le Gris² has made a number of contact alloys, doing the work on a somewhat different plan. He melts one metal and very carefully pours the other metal, also molten, on top of the first; thence, by rate of cooling, he is able to limit the depth of diffusion. He gives numerous photomicrographs to show results on several systems of the lower melting metals. Le Chatlier³ has done similar work in which he has attempted to obtain the whole series of any one system in a single melt.

¹ Bruni and Meneghini, Intern. Zeit. Metallographie, 11 (1911) p. 26

² Le Gris, Rev. metallurgie, 8, p. 613

³ Le Chatlier, Int. Assoc. f. Test. Mat. II (1912) p. 12

(2) Cementation or Carbonization of Metals.

This is a process of diffusion which has been known and practiced in the case of iron since ancient times. Here again C. H. Desch¹ has made an excellent summary of the work which has been done. However, the process is so well known and generally understood that it is not deemed necessary to discuss it at length here. One phase of the question might, however, be worthy of mention; that is, the cementation of iron by gaseous hydrocarbons and carbon monoxide. This was first tried out by A. Ledebur². He found that, although the gases do not penetrate to the interior of the metal, carbonization is much more rapid than in the case of solid materials, and also that it may be carried out at a much lower temperature. This may well be explained by the fact that the carbon does not diffuse as free carbon, but as the carbide of the metal, which would be more readily formed by the gaseous carbonizer.

One other point must be considered in the carbonization of iron, which may or may not be of importance in the carbonization of other metals. This is the fact that iron carbide is not appreciably soluble in alpha iron. Since this is the case, to secure rapid and stronger carbonization, it is necessary to carry the heating above the temperature range of alpha iron--690° to 760° C.

It is quite probably that a form of tungsten exists above the equi-axing temperature (1800° C.) which absorbs the carbide more readily than the form which exists below this temperature.

¹ C. H. Desch, Chem. News 106 (1912) p. 178

² A. Ledebur, Stahl und Eisen, 26 (1906) p. 72

(3) Commercial Applications of Diffusion.

Alloys formed by diffusion have been made the basis for the development of several commercial processes involving the coating of one metal with another. The more important of these are as follows:

a. Sherardizing¹, in which the article to be coated is packed in zinc dust and heated at 250°-300° C. in rotating drums. The zinc diffuses slowly into the iron, forming an alloy on the surface, which is very resistant to oxidation.

b. Calorizing², in which powdered aluminum is substituted for the zinc. The purpose of the alloy formed is to resist oxidation at high temperatures.

c. Electroplating. The coating formed slowly diffuses into the metal upon which it is deposited.

d. Formation of a corrosion-resisting surface³ on metallic articles, by heating with silicon at temperatures below the melting point of the metal, preferably between 700° and 1350° C. for a period of from 24 to 72 hours.

e. Case-hardening.

¹ Sherardizing, Met. and Chem. Eng. 14, p. 683

² Calorizing, Trans. Am. Electro-Chem. Soc. 27
(1915) Gen. Elec. Rev. 17, p. 949

³ Formation of a corrosion-resisting surface on
metallic articles, Allen, U. S. Pat. 981,513

3. The Outline of the Present Investigation.

(1) Various types of furnaces have been considered and three have been adopted for this work.

(2) The following series of binary alloys have been prepared by diffusion: aluminum-tungsten, copper-tungsten, antimony-tungsten, cadmium-tungsten, tin-tungsten, zinc-tungsten, and carbon-tungsten.

(3) The following series of ternary alloys have been prepared by diffusion: iron-tungsten-carbon, chromium-tungsten-carbon, and nickel-tungsten-carbon.

(4) All alloys have been studied microscopically and those giving results of value have been photographed.

II. EXPERIMENTAL

1. Method of Procedure.

(1) Methods Used for the Preparation of Alloys.

Heretofore, practically all of the work on tungsten alloys has been by the reduction of the oxides of the metals, in the presence of each other, with hydrogen or carbon and by the use of this heat to secure in part the high temperatures which are needed in this work. A typical illustration of this method is the work of C. L. Sargent in his thesis for the degree of Doctor of Philosophy¹, "The Production of Alloys of Tungsten and Molybdenum in the Electric Furnace".

This method is due largely to the very high melting point of tungsten (3350° C.) and its consequently lower activity at the ordinary temperatures obtained. This has, however, in the present investigation been overcome by raising the temperature of the alloying metal to a point at which the vapor pressure will be sufficiently high to allow diffusion to take place. A table of vapor pressures of the several metals, with corresponding temperatures, has been taken from the work of John Johnson². The temperatures at which alloys have been prepared, especially in the case of the more volatile metals, have been decided upon after a consideration of this table, and an attempt has been made to approximate the same vapor pressure with the different metals. The vapor pressure of tungsten³ is practically negligible at these

¹ Thesis for Ph.D. Univ. of Pa. (1900)

² John Johnson, J. I. E. C. 9, (1917) p. 873

³ Vapor pressure of tungsten, Langmuir; Phys. Rev. 2, (1913) p. 322 & Phys. Rev. 4, (1914) p. 377

temperatures.

The general plan for the preparation of the alloys has been to pack a piece of tungsten, approximately a quarter-inch cube, with the alloying material in as finely a divided form as possible. If hydrogen atmosphere was to be used, no protective covering was necessary, but in other cases powdered retort carbon was used as a cover.

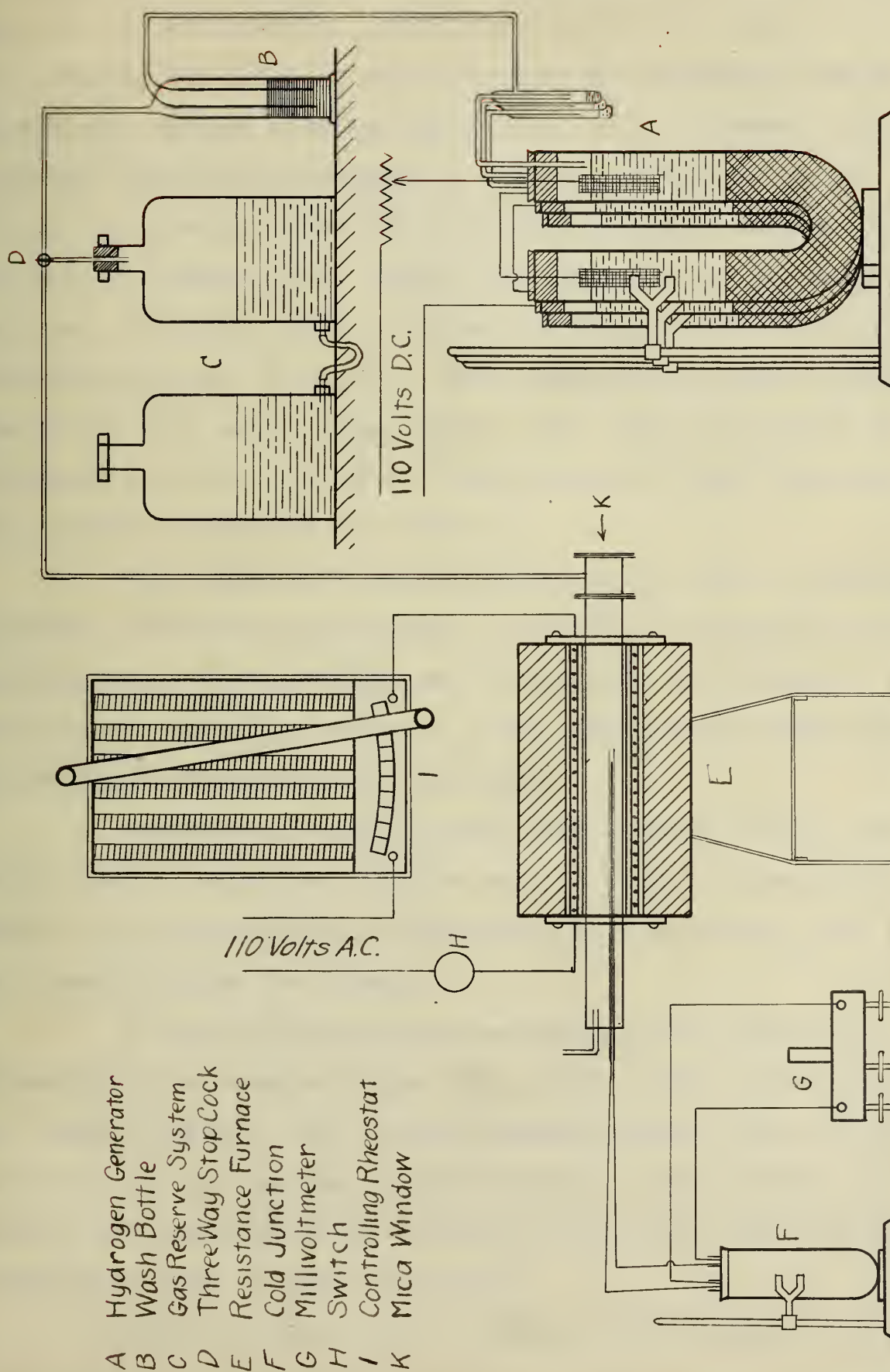
Time and temperature were separately considered in the case of each system. The reasons for temperatures used have already been explained.

The original plan for the duration of the tests was to make a short test, one to two hours, and, if this test showed any indications of diffusion, to make a twenty-four to thirty-six hour run on the same system. This has been followed wherever practicable.

2. Apparatus.

(1) Three furnaces have been used in this work.

a. A resistance furnace (Fig. I.) in which a porcelain tube, fitted with gas-tight connections, was used in order to maintain a proper atmosphere for the treatment which was to be carried out. An electrolytic hydrogen generator, consisting of three U-tube generators in series, using nickel electrodes and an electrolyte of 10% NaOH solution, and requiring about three amperes of current to operate most efficiently, was used as a source of hydrogen. Sufficient hydrogen was generated before heating up the furnace to sweep out thoroughly all air from the furnace. This supply of hydrogen was stored in a large aspirator bottle connected into the line by a three-way stop-cock. It



- A Hydrogen Generator
- B Wash Bottle
- C Gas Reserve System
- D ThreeWay StopCock
- E Resistance Furnace
- F Cold Junction
- G Millivoltmeter
- H Switch
- I Controlling Rheostat
- K Mica Window

FIG 1.

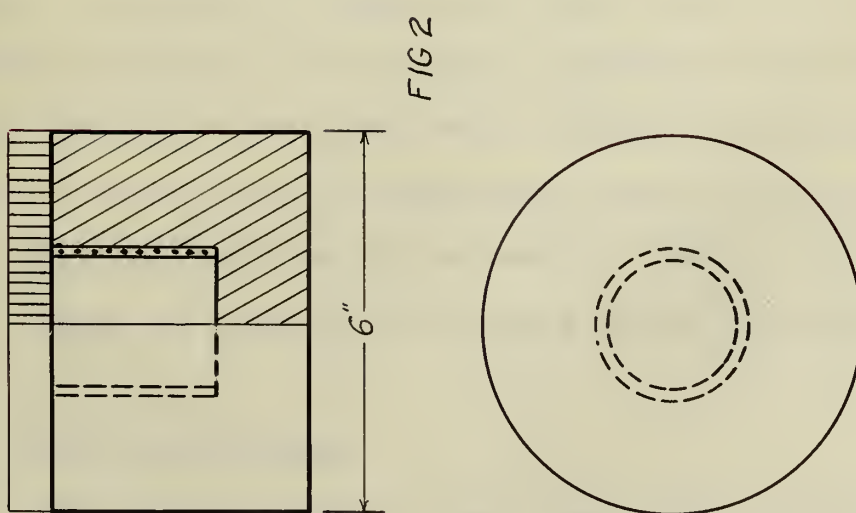
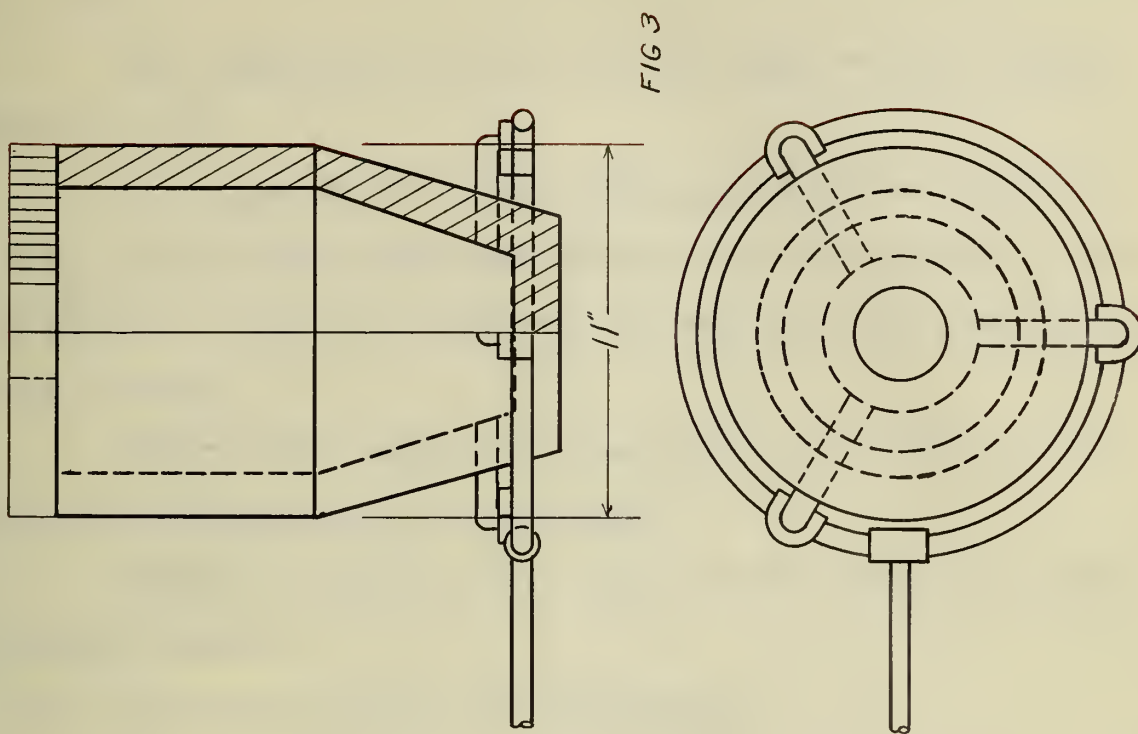
could then be forced rapidly through the furnace, sweeping out all air very efficiently. After the air had been driven out of the furnace, the hydrogen was allowed to flow directly from the generators, through alkaline pyrogallol, to the furnace. This flow was sufficient to maintain a reducing atmosphere in the tube. The porcelain tube was surrounded by one of alundum which carried the heating unit. During the first part of the work, this unit was a platinum ribbon resistance winding, using about 1.5 kilowatts per hour at 1100° C. This was later replaced by a winding of No. 14 B. and S. gage Chromel wire, which used about 2.5 kilowatts per hour at 1200° C. The heating unit was surrounded by a jacket of magnesia and asbestos.

The temperature was controlled by the use of a platinum-platinum 10% rhodium thermocouple, accurately calibrated in connection with a Siemens-Halske millivoltmeter. No attempt at control closer than 5° C. was made, since very accurate temperature control was not necessary in this work.

Treatments in this furnace were carried out in a porcelain boat in which the tungsten was surrounded by the alloying metal, or, in carbonization treatments, by illuminating gas, which was passed through the furnace.

b. The second furnace used was a small Hoskins nichrome-wound resistance furnace (Fig. II.), using one kilowatt per hour at 1200° C. The heating chamber was two inches in diameter and two and one-half inches in depth. This furnace was used in the twenty-four and thirty-six hour tests, where temperatures up to 1200° C. were being used.

In the preparation of alloys in this furnace, Dixon



graphite crucibles were used, and powdered retort carbon was used as a cover.

The temperature control was the same as that used in furnace No. I.

c. A gas fired furnace (Fig. III.) of the pot type was used in all tests requiring temperatures above 1200° C. and up to 1600° C. Fig. III. sufficiently explains the construction of this furnace.

Temperature measurement was made here by the use of a Leeds and Northrup optical pyrometer.

Graphite crucibles were used and the alloy protected by powdered carbon.

(2) Grinding and Polishing Apparatus.

The grinding was done on a machine carrying four grades of emery wheels. After a specimen had been ground down on the emery wheels, it was polished successively on numbers 1, 0, 00, and 000 emery paper. The 0000 grade of emery paper has generally been found to scratch the specimen, and therefore it has not been used. After polishing on 000 paper, specimens were further polished on broadcloth saturated with levigated alumina #2. This has proved a very quick and excellent method of polishing, especially when the hardness encountered in these alloys is considered. Rouge on broadcloth was used in the final polishing process.

(3) Etching Reagents.

Two etching reagents have been used: hydrofluoric acid, containing a few drops of nitric acid, and boiling hydrogen peroxide. Only a very few seconds time are required in the case of

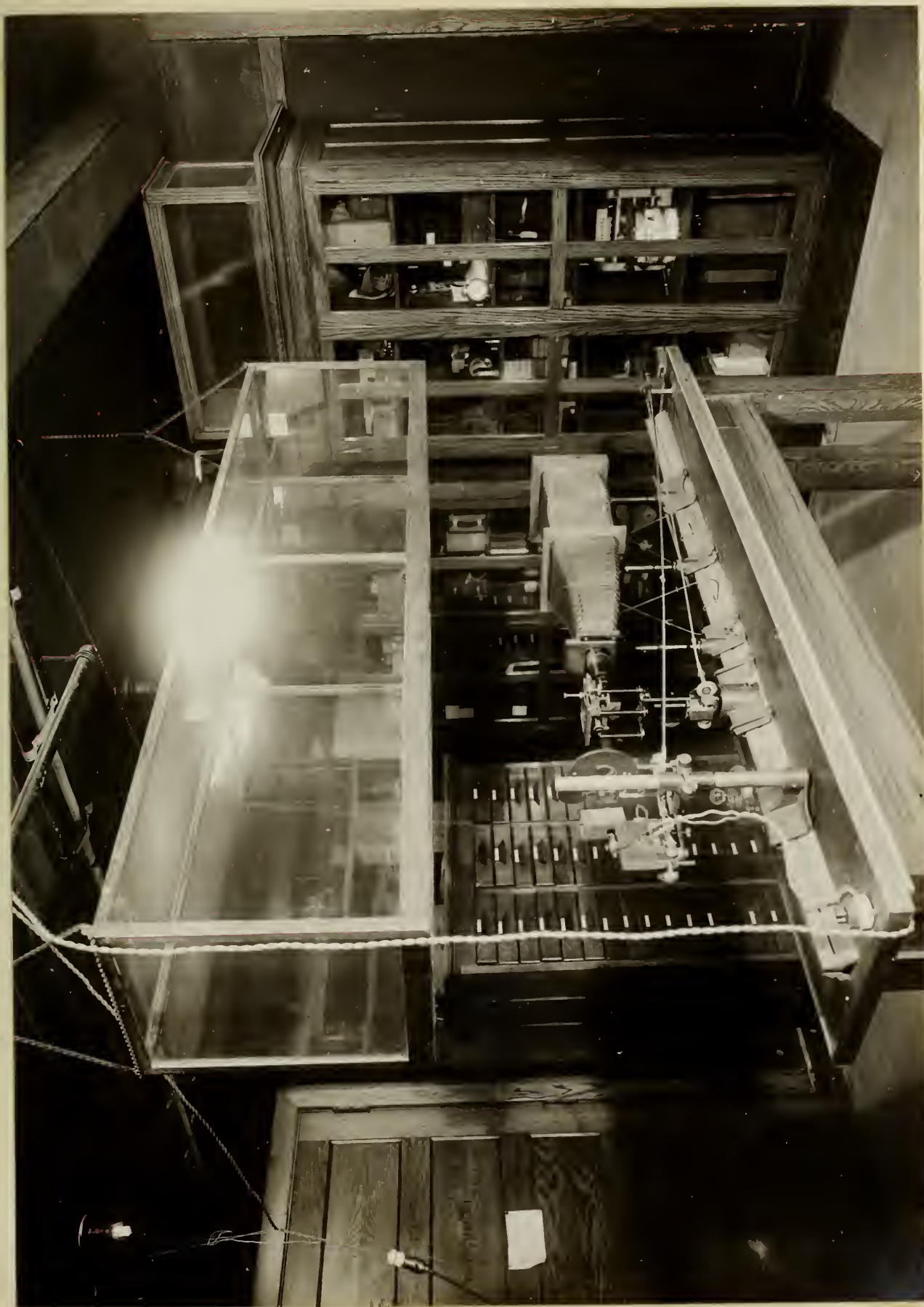


Fig. IV Leitz Metallograph

the hydrofluoric acid, while, in the case of the hydrogen peroxide, about thirty to sixty seconds are required.

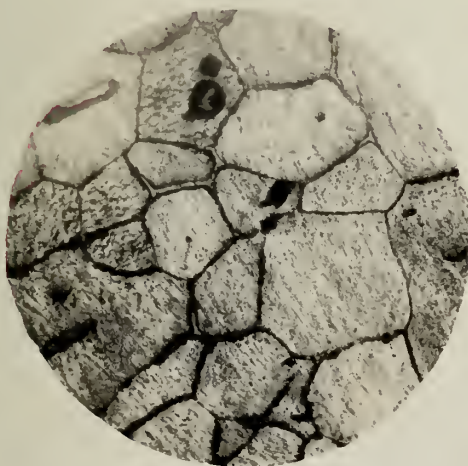
(4) Photographic Apparatus.

All photomicrographs have been taken with a Leitz Metallograph (Fig. IV.), using a carbon arc as the source of light. This instrument is well equipped with all sizes of objectives and eyepieces, including apochromatic objectives, correction eyepieces, and micro summaries.

(5) Material.

The tungsten used in this work was procured from the

Fansteel Products Company of North Chicago, Illinois. It was in the form of sintered bars. The microstructure of one which has been overheated in sintering is shown in Fig. V.



Other metals were of commercial quality and were procured in as finely divided a form as was obtainable.

FIG. V.

Magnification, 100 diameters

3. Results of Experiments and Discussion.

(1) Binary Alloys.

a. Alloys of tungsten and aluminum.

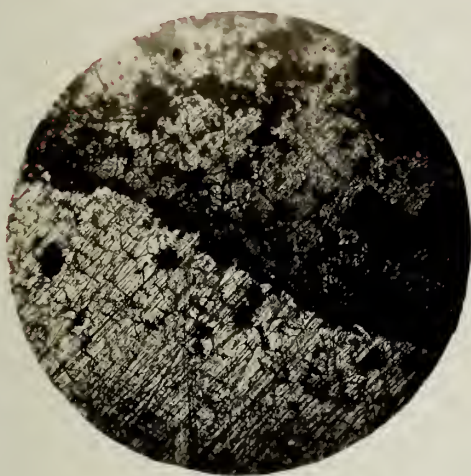


Fig. VI.

Experiment I.

Furnace No. 1
 Time 8 hours
 Temperature 800° C.
 Etched HF
 Photomicrograph . . x 100

This specimen shows a marked diffusion at the junction between the two metals. The lighter portion is the tungsten and shows the diffusion around the grain boundaries very plainly.

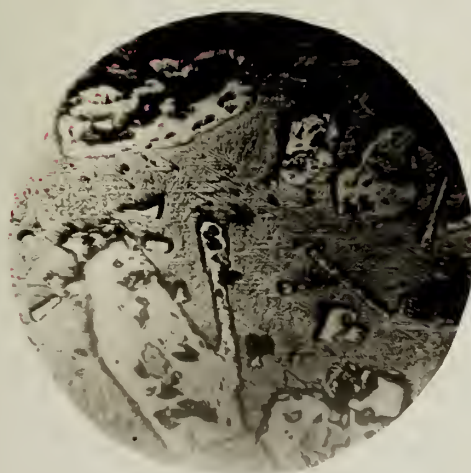


Fig. VII.

Experiment 2

Furnace No. 2
 Time 36 hours
 Temperature 1200° C.
 Unetched
 Photomicrograph . . x 100

This specimen shows the formation of two distinct intermetallic compounds, a monoclinic crystal and a hexagonal crystal. Campbell and Mathews¹, by analysis, have shown these

to be respectively WAl_5 (50% W) and WAl_7 (58% W). Figure VIII. shows a crystal of the compound WAl_7 , magnified 355 diameters. The dark portions in this figure are holes due to inclusions of carbon.

Experiment 3.

tungsten powder added to molten aluminum.

Furnace No. 2

Time 2 hours

Temperature 1200° C.

The specimen was not examined microscopically nor was it photographed. It showed, however, distinct crystals



Fig. VIII.

of both kinds.

The excess aluminum was dissolved out with dilute HCl and, by the use of a hand lens, these could be easily separated.

The crystals were very hard and also very resistant to acid. They were not attacked by HCl or H_2SO_4 .

¹ Campbell and Mathews, J. A. C. S. 24 (1902) p. 256

b. Tungsten and copper.

Experiment 1.

Furnace No. 1
 Time 2 hours
 Temperature 1100° C.
 Etched HF

The specimen showed no apparent diffusion; so it was not photographed.

Experiment 2.

Furnace No. 2.
 Time 36 hours
 Temperature 1150° C.
 Etched HF
 Photomicrograph . . . x 100

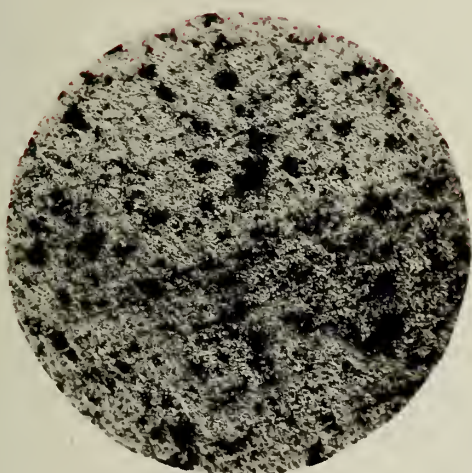


Fig. IX.

Fig. IX. shows the results of this experiment. The darker portions indicate the alloy rich in copper, which has been somewhat more readily attacked by the etching reagent.

c. Tungsten and antimony.

Experiment 1.

Furnace No. 2
 Time 2 hours
 Temperature 1050° C
 Etched HF
 Photomicrograph . . x 100

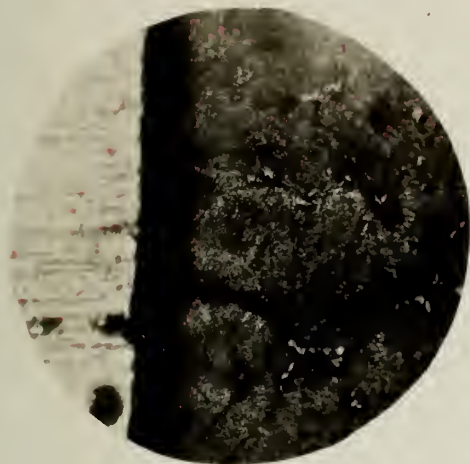


Fig. X.

Figure X shows the diffusion of the tungsten between the grain boundaries of the antimony. The dark band at the junction of the two metals is due to the uneven etching of the two metals. The diffusion in this case extended about one-eighth of an inch in from the edge of the tungsten.

Experiment 2.

Furnace No. 2
 Time 24 hours
 Temperature 1050° C.
 Etched 4% Alc.
 HNO₃

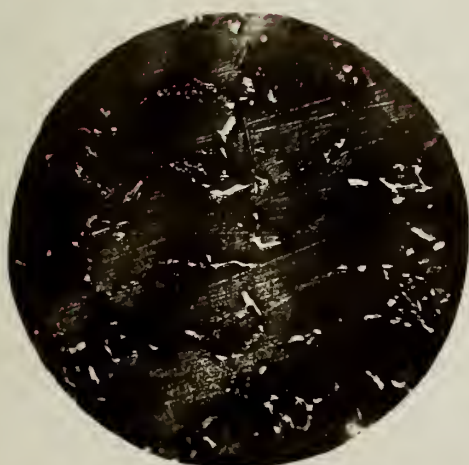


Fig. XI.

Fig. XI. shows the more complete diffusion, the beginning of which was evident in Experiment 1. Here the diffusion was uniform through-

out the antimony, showing that the system has reached an equilibrium under the existing conditions.

d. Tungsten and cadmium.

Experiment 1.

Furnace No. 2
 Time 1 hour
 Temperature 500° C.
 Unetched
 Photomicrograph . . x 100

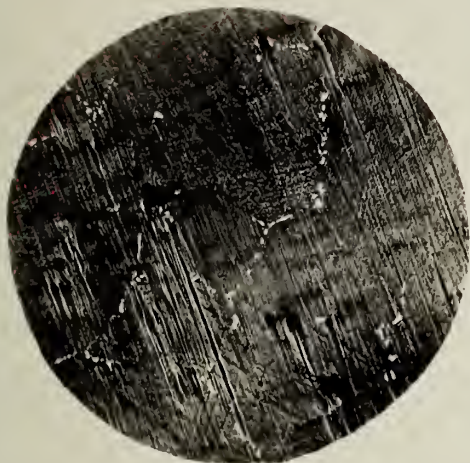


Fig. XII.

Fig. XII. shows the results of the experiment. The action has been practically the same as in the case of the antimony-tungsten, except that the higher vapor pressure of the cadmium causes the reaction to proceed more rapidly.

e. Tungsten and zinc.

Furnace No. 1
 Time 2 hours
 Temperature 600° C.
 Etched HF

The results of this experiment were not definite, and a photomicrograph was not taken. There was, however, a very slight alloying effect of the zinc on the tungsten.

f. Tungsten and tin.

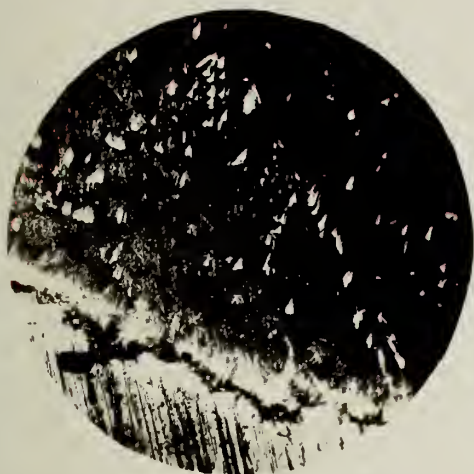


Fig. XIII.

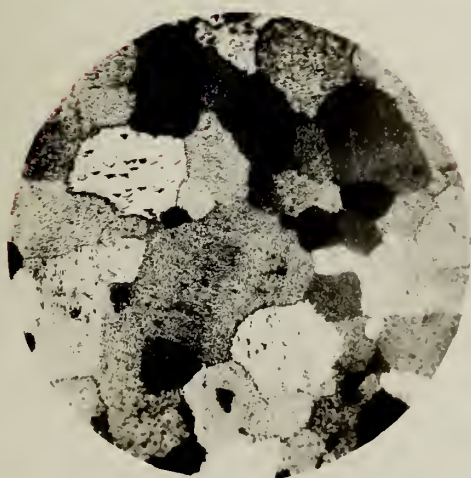


Fig. XIV.

Experiment I

Furnace No. 2
 Time 1 hour
 Temperature 900° C.
 Etched HF
 Photomicrograph . . x 100

Fig. XIII. shows the form of a white tungsten alloy at the junction of the metals. This alloy has been diffused into the tin and also to a slight extent into the tungsten. The depth of diffusion into the tin was about one-eighth of an inch.

Fig. XIV. shows the structure of the tin beyond the depth of the formation of the alloy, after very slight etching.

g. Tungsten and carbon.

Jeffries¹ states that tungsten, at high temperatures, in the presence of carbonaceous gases, forms tungsten carbide, generally W_2C , and, at higher temperatures, in the presence of solid carbon. He shows microphotographs of tungsten carbonized in the presence of hydrocarbons at $1100^\circ C$, and in the presence of solid carbon at $1800^\circ C$.

Moissan² has formed the carbide W_2C by the reduction of WO_3 with an excess of carbon in an arc of 900 amperes at 50 volts. This is not, however, of much importance here, since the process is not one of diffusion.

The carbon-tungsten system has been quite thoroughly investigated by Ruff and Wunsch³, who establish the existence of three carbides of tungsten: WC , W_2C , and W_3C . They state that the solubility of the carbide in the tungsten is extremely slight, since, with as low as .12% C, a eutectic alloy forms at the boundary of the crystals and, with 1.43% C, the eutectic quite obliterates all other structures. They give photomicrographs of tungsten-carbon alloys, varying from pure tungsten to an alloy containing 3.88% carbon. The alloys were prepared by sintering powdered tungsten, containing free carbon. These were subsequently heated, in an atmosphere of hydrogen until the equi-axing temperature was reached, in an electric arc.

The above data would lead to the conclusion that a form of tungsten exists, above the equi-axing temperature, in which the

¹ Jeffries, Trans. Am. Inst. Min. Met. Eng. IX. (1919) p. 588

² H. Moissan, Compt. rend. 123 (1896) p. 15

³ O. Ruff and R. Wunsch, Zeit. f. Anorg. Chem. 85 (1914) p. 292

carbide is more readily soluble than in the form which exists at lower temperatures.

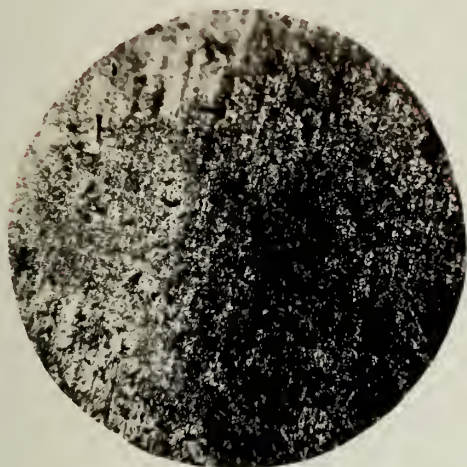


Fig. XV.

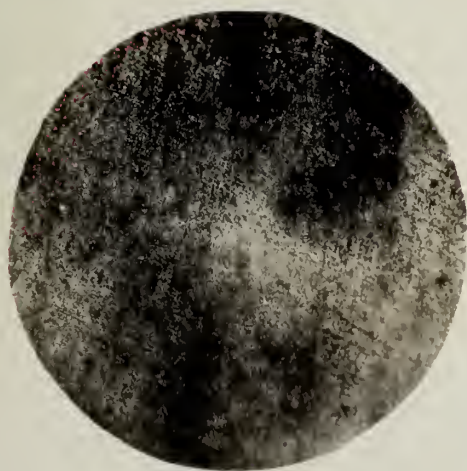


Fig. XVI.

Experiment 1

Furnace No. 1
 Time 2 hours
 Temperature 1000° C.
 Atmosphere Hydrocar-
 bon
 Etched H₂O₂
 Photomicrograph . . x 100

This specimen showed macroscopically a formation of carbide to the depth of about one-sixteenth of an inch. However, upon polishing and etching, the carbide did not show up well, since the contrast between the constituents is slight. The results are as shown in Fig. XV.

Experiment 2.

Furnace No. 3
 Time 8 hours
 Temperature 1600° C.
 Carbonizer D. C. L.
 Etched H₂O₂
 Photomicrograph . . x 355

It was thought that, by using the D. C. L. commercial

carbonizer, which contains a very active form of carbon, together with some organic carbon compounds, it might be possible to carbonize the tungsten at this temperature. The specimen (Fig. XVI.), however, shows no carbonization,

Experiment 3.

Charge surrounded by thermite

Time approximately 15 min.

Temperature 2700° C

Etched H_2O_2

Photomicrograph . . . x 100

Fig. XVII.

The specimen was packed in powdered carbon in a small

graphite crucible. This was in turn surrounded by 200 grams of thermite contained in a larger crucible. The charge was ignited and the crucible covered, allowing it to cool undisturbed. The time at the high temperature attained was sufficient to secure a slight carbonization, as shown in Fig. XVII.

Generally speaking, the work on the primary carbides has not been very successful, due to inadequate facilities for attaining the high temperatures necessary in this work.

(2) Ternary Alloys.

a. Iron, tungsten, and carbon.

The purpose in considering these systems was to form, if possible, the double carbides similar to those formed in "high speed" steels. It was thought that this carbide, with its very great hardness, might be formed on the surface of the tungsten, and thus develop properties which might prove valuable where such a hardness is desired.

The importance of the system cannot be overestimated, since it forms the basis of the principle "high speed" steels which are in use today.

Experiment 1

Furnace No. 3
 Time 2 hours
 Temperature 1600° C.
 Etched HF
 Photomicrograph . . x 355

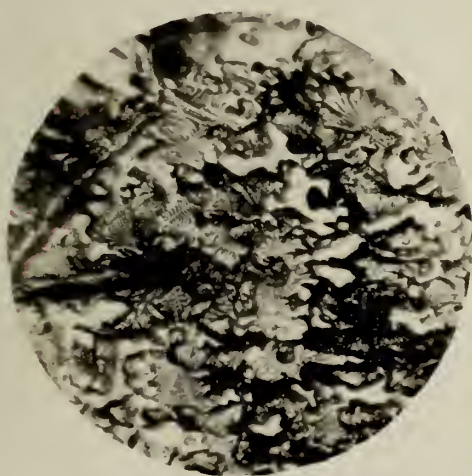


Fig. XVIII.

The alloy contained sufficient iron, so that the tungsten was dissolved and the alloy melted. It was allowed to cool quickly from a high temperature. Figure XVIII. shows the presence of a eutectic alloy. It is probable that the lighter portions show the formation of a double carbide, since the alloy was made in an

excess of carbon.

Experiment 2

Furnace No. 3

Time 10 hours

Temperature 1500° C

Unetched

Photomicrograph . . x 100

Complete fusion resulted.

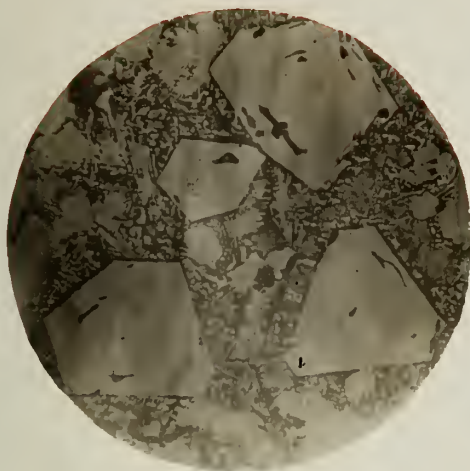


Fig. XIX.



Fig. XX.

Figs. XIX. and XX. show the microstructure of this alloy. The photographs were taken of planes at right angles to each other. Fig. XIX. shows the same form of crystal which is present in a high tungsten steel which has been cooled slowly. The crystals, however, are larger in this alloy, due to the slower rate of cooling and the higher percentage of tungsten present. This would point to the fact that crystals are a tungstide of iron, rather than the double carbide.

R. A. Hadfield¹ has established the existence of a

¹ R. A. Hadfield, J. Iron and Steel Inst. 64, 2
(1903) p. 14

compound Fe_4W and a double carbide $\text{Fe}_3\text{W}_3\text{C}_3$. The compound, which he designates as Fe_4W , is similar in crystalline form to that shown in Fig. XIX.

b. Chromium, tungsten, and carbon.

Experiment 1.

Furnace No. 3
 Time 12 hours
 Temperature 1450°C .
 Etched HF
 Photomicrograph . . x 330

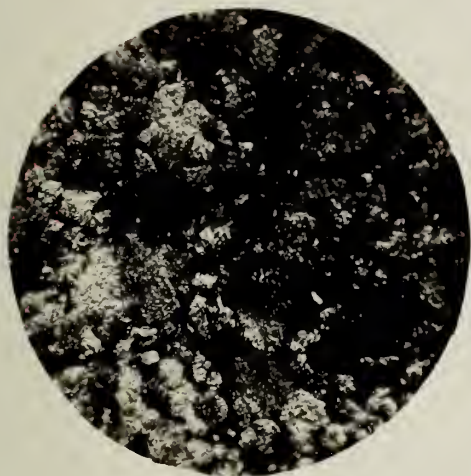


Fig. XXI.

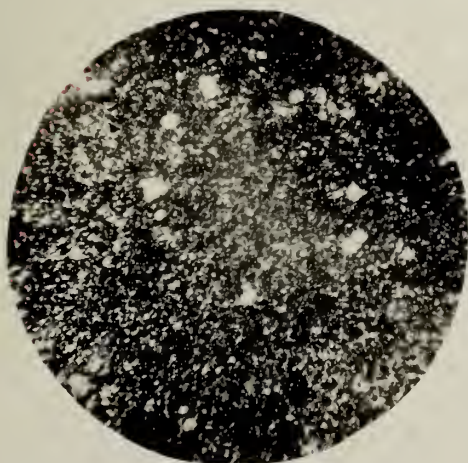


Fig. XXII.

The results of this experiment were such that the specimen offered the greatest difficulty in grinding and polishing, since it was of a very high abrasive hardness. It also possessed a high scratch hardness, scratching glass quite readily, and was only scratched by the emery grinding wheels, when a heavy pressure was applied. Fig. XXI. shows the microstructure. The lighter portions denote the carbide which has been formed. The specimen showed a strong resistance to the etching acid.

Experiment 2.

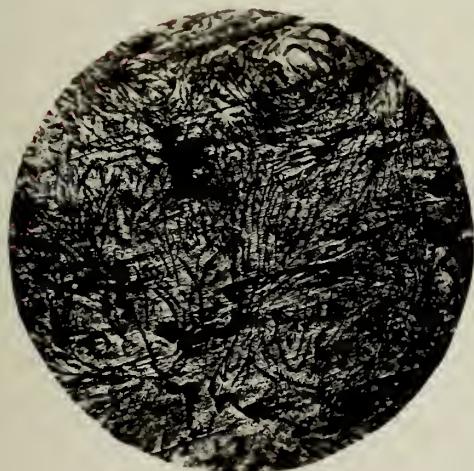
Furnace No. 3
 Time 10 hours
 Temperature 1500° C.
 Etched HF
 Photomicrograph x 60

Fig. XXII. shows the microstructure of the alloy. The results are practically the same as in Experiment 1.

c. Nickel, tungsten, carbon.

Experiment 1

Furnace No. 3
 Time 2 hours
 Temperature 1600° C.
 Etched HF
 Photomicrograph . . x 100



The microstructure of this alloy is shown in Fig. XXIII. The dark lines indicate the separation of carbon as free graphite from a matrix of a tungsten-nickel alloy.

Fig. XXIII.

MEMORANDUM

TO : THE SECRETARY OF THE ARMY
FROM : THE CHIEF OF STAFF
SUBJECT: [Illegible]

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Experiment 2

Furnace No. 3
 Time 10 hours
 Temperature 1500° C.
 Unetched
 Photomicrograph . . x 100



Fig. XXIV.

This alloy is somewhat higher in tungsten than alloy 1. The time of heating has also been increased. The microstructure (Fig. XXIV.) seems to show the formation of the double carbide on long heating in this system, as shown by lighter portions of picture. Complete

fusion has occurred in the case of both alloys. The matrix in Fig. XXIV. is a tungsten-nickel alloy rich in tungsten.

III. Summary

1. A set of three furnaces has been arranged in which the various requirements of this problem, as to time, temperature, reducing atmosphere, and temperature control, have been largely met.
2. A series of binary diffusion alloys of tungsten have been prepared and studied.
3. A series of ternary diffusion alloys have been prepared and studied.

IV. Conclusions

1. Tungsten forms diffusion alloys quite readily with the following metals: tin, antimony, cadmium, aluminum, iron, and nickel.
2. Distinct inter-metallic compounds are formed in the case of the tungsten-aluminum and tungsten-iron alloys.
3. A very hard alloy is formed by diffusion with the chromium-tungsten-carbon system. This is probably a mixture of the single carbides of tungsten, together with the double carbide of tungsten and chromium.
4. Assembled data on the carbides of tungsten lead to the conclusion that a form of tungsten exists above the equi-axing temperature in which the carbides are more readily soluble than in the form which exists below this temperature.
5. Copper diffuses rather slowly and does not form an alloy of any characteristic properties which might be used to establish the identity of the same.
6. Due to the wide range of the investigation, the work, necessarily, has resulted in little more than a survey of the field.

This has, however, been sufficient in most cases to show the feasibility of a more complete investigation in certain systems. It is the opinion of the author that further work on the systems aluminum-tungsten, tin-tungsten, chromium-tungsten-carbon, and nickel-tungsten-carbon would give results of value.

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